International Journal of Engineering Education Vol. 35, No. 1(B), pp. 372–384, 2019
Printed in Great Britain
0949-149X/91 $3.00+0.00

Learning in Engineering through Design, Construction, Analysis and Experimentation*

M. M. PASTOR, F. ROURE, M. FERRER, X. AYNETO, M. CASAFONT, J. M. PONS and J. BONADA
Barcelona School of Industrial Engineering (ETSEIB), Polytechnic University of Catalonia (UPC), Department of Strength of Materials and Structural Engineering, Spain. E-mail: {m.magdalena.pastor; francesc.roure; miquel.ferrer; javier.ayneto; miquel.casafont; josep.maria.pons; jordi.bonada}@upc.edu

The experience presented is part of the teaching of two subjects of the Mechanics discipline: Continuum Mechanics and Strength of Materials, in the field of Mechanical and Industrial Engineering. In the bachelor's degree at the ETSEIB-UPC, the first semester of the third academic year is devoted to Continuum Mechanics and the second one to Strength of Materials. Both subjects integrate theory and practice: applications, lab and coursework. The article focuses on the coursework or also named course project, which consists of designing/optimizing, analysing, manufacturing and testing a mechanical/structural element subject to stresses and strains. This paper aims at showing the benefits of combining practice, theory, simulation and experimentation, as well as some of the limitations and difficulties encountered in its implementation, such as the evaluation of the degree of involvement of each team member and the lack of correlation between the mark of the coursework and examinations' scores. An important conclusion is that students enjoy the project, get deeply involved and work hard, making the subject more attractive.

Keywords: active problem-based learning, hands-on learning experiences, innovation in engineering education

1. Introduction

Ten years ago the Engineering School of Barcelona (Escola Tècnica Superior d'Enginyeria Industrial de Barcelona, ETSEIB—Universitat Politècnica de Catalunya, UPC) was about to define a new curriculum for the Industrial Engineering Degree. This is a multidisciplinary degree, covering many industrial fields, like Mechanics, Electrics, Electronics, Robotics, Chemistry, Materials, Industrial Buildings, Energy, Industrial Management, Bioengineering, etc. The degree has a curriculum of 4 years, including a Final Project Work in the second semester of the 4th year. In the first two years, students get a very good scientific basis. Then in the third and fourth year, a wide variety of applied sciences and basic technologies build up the multidisciplinary and transversal profile of the degree. After graduating, our students usually get good jobs, because of their multidisciplinary technical profile, with a good scientific basis. Nevertheless, before defining a new profile to adapt it to the requirements of the European Higher Education Area (Bologna), the School decided to do a survey to employers and former students about the strong and the weak points of the profile of our graduates. The results of this survey revealed that the main deficits of our graduates were in soft skills, rather than in knowledge, especially in three aspects: application of the theory knowledge to the solution of practical problems, team working, and oral and written communication.

Therefore, it was decided to introduce simultaneously several innovations in the curriculum to solve these deficits: (1) By introducing two new subjects, called Project 1 and Project 2, in the second semester of the 2nd and 3rd year, respectively. These two subjects are project-based, designed for the application of the knowledge acquired by students in previous subjects. (2) By fostering the introduction of a coursework in theory subjects to force students to apply their knowledge to the resolution of practical problems or to the design of simple components or devices.

The real benefits of introducing project-based learning into an engineering curriculum can only be achieved when combined adequately with class-based learning (theory and problems).

In subjects such as Continuous Mechanics and Strength of Materials, with a strong physical and mathematical load, a good theoretical basis is needed before attempting to analyse or solve any problem or project, if it is to be treated as a true "engineering" issue. Otherwise, there is a risk of an overly naive approach to the design and analysis aspects of the proposed issues. Therefore, the overall success of introducing project-based learning is the appropriate distribution of projects throughout the curriculum. It can be started with a project as early as the first year, but the difficulty and subject matter must be carefully selected according to the knowledge and maturity of the students. The introduction of these two course projects into the subjects, after having presented the theoretical

* Accepted 29 October 2018.

concepts, shortly after having been learned, seems to be a good practice to improve the benefits of project-based learning.

In this paper, the experience of introducing the coursework in the subjects of Continuum Mechanics and Strength of Materials is presented. In the ETSEIB-UPC curriculum, Continuum Mechanics is studied in the first semester and Strength of Materials in the second one, of the 3rd academic year. Both of them are compulsory subjects for all the students of the Industrial Engineering Degree. About 200 ÷ 240 students are enrolled in the course, distributed in four groups for theory lectures, and these, in turn, are divided in four groups of lab/experimental activities with a maximum of 15 students each one.

The coursework consists of designing/optimizing, analysing, manufacturing and testing a mechanical/structural element subject to stresses and strains, and is developed by teams of three students. Each team has to present the output of the work in oral and written form.

High levels of Bloom's taxonomy are implemented in these projects:

- Applying: using the knowledge acquired to new situations
- Analysing: how material and geometric properties influence on the behaviour of the designed object.
- Evaluating: which is the best option to meet the required criteria in terms of stresses and strains.
- Creating: the work consists precisely in "designing, constructing, planning, producing, designing and processing" a mechanical or structural element under load conditions.

The two forms of Kolb's experiential learning model are also implemented: abstract learning (AC) through conceptualization and generalizations provided in theoretical classes, and concrete experience (CE) materialized in the courses described here. With the two ways of transforming these experiences: actively experiencing what has been learned in a new situation (design of a resistant element) and fostering analysis, thinking and comprehension (how to meet the imposed design criteria).

Experiences addressed in Mechanical Engineering demonstrate benefits of assimilating Hands-on methodologies in subjects or curricula. Several methods to categorize student's learning styles and models of the learning process, as Kolb cycle and Bloom's taxonomy, are applied in [1]. Cooperative project-based learning as education methodology for incorporating competences in engineering higher education is presented in [2]. Elements of each of the six Bloom's competencies (knowledge, comprehension, application, analysis, synthesis and evaluation) are developed explicitly in this—engineering mechanics module [3]. [4] Points out as positive key themes, among others, a practical opportunity to gain skills in preparation for professional practice, the opportunity to "learn by doing" and a group-work experience. Design Spine, a multidisciplinary experience focused to project-oriented courses, can be an effective method for teaching engineering design [5]. This study [6] compares both traditional classroom lecture and CHAPL (Cooperative Hands-on Active Problem-based Learning) through a survey addressed to students to assess their perspectives. Experiential learning methodology enhances students' learning outcomes; the class pass percentage and grade score are better, and the class attendance is higher, compared with traditional lecturing methodology [7]. Design, modelling and manufacturing of an instructional module for the use in the classroom, is an alternative to standard lecture [8].

[9, 10, 11] report benefits about including engineering analysis and FEA (Finite Element Analysis) in design in Mechanical Engineering Curricula. It is stated or concluded that the use of the finite element method enables students to solve advanced problems in stress analysis [9]. In [10] it is suggested that different competencies should be integrated into subjects and not be taught as a separated subject. ALM (Active Learning Modules) contribute to improvement of aptitude and comprehension of contents in engineering [11].

References [12] to [15] include projects with design, analysis and FEA, as well as comparison of experimental results with analytical and/or FEA predictions. In [12], a survey completed by students indicated that learning experiences obtained from the project were valued as much as traditional classroom lectures combined with working homework problems. A comparison between hand calculations and FEA as design tools to predict experimental results is presented in [13]. Students working on mechanical design projects face to analogical thinking, prototyping and testing, modelling and analysis, and tolerating uncertainty [14]. Teaching students by way of case studies in engineering courses is key to achieve competencies in several branches of engineering design, as materials, structural analysis, numerical and experimental analysis [15].

These works [12] to [15] are the most similar to the course projects presented in this paper.

Regarding findings on approach experimental projects in Strength of Materials courses, [16] claims that solving a real-life project motivates students because they learn as theoretical concepts taught are applied and multiple valid solutions can be found. Furthermore, students and lecturers agree in that the Multiple Approach Experimental Project (MAEP) is useful for reinforcing the theoretical concepts previously explained in the classroom [17].

Active learning methodologies are essential in engineering since they constitute an important means of effective assimilation of theoretical concepts by students. For example, the recommendation in the Educating the Engineer of 2020 calls for creating learning environments "in which students (1) were more actively engaged than taking notes, (2) focused on problems, design challenges and artefacts in addition to concepts, and (3) often worked with other students to understand and complete assigned tasks" [18].

The motivational component that inductive learning, and especially project-based learning, offers in response to challenges that simulate real professional situations, cannot be achieved through theory classes [19, 20]. In this regard, the study conducted by VDI in collaboration with ASME [21] on the skills to be developed for engineering in the context of industry 4.0 emphasizes the importance of practical experience, close to the work reality, in the education of future professionals.

This type of training allows the development of other transversal skills, such as complex problem solving, critical thinking, creativity, teamwork or conflict resolution. Such skills are of great value to the profession and necessary for the new paradigm of industry 4.0 [22], but they can hardly be developed by the traditional teaching methods used in conventional classes.

The materialization of concepts in the form of physical objects that students design, simulate, construct and test is undoubtedly an extraordinary complement to the consolidation of theoretical learning and to the development of real-life problem-solving skills.

In order to promote complex problem-solving skills, we do not start from a well-defined statement with a single answer, but from an open proposal on which students should investigate until a solution is found in terms of geometry, materials, manufacturing process, etc. At the same time, students are introduced to the use of numerical simulation technologies based on the application of theoretical concepts previously presented in class. The resolution of a real situation instead of a theoretical problem helps greatly to the correct assimilation of knowledge.

At a later stage of the work, students use their critical thinking skills through a reasoned analysis of the results of both the simulation and the subsequent testing of a functional prototype.

The entire project at the same time fosters the creative abilities of the students, both in the initial design and for its subsequent optimization.

Finally, the physical realization of a prototype that can be tested adds a component of hands-on knowledge to the whole process and mitigates the danger of overly moving students away from physical reality and the real problems that engineers encounter in transforming their ideas into reality. 3D printing is currently being incorporated into this phase, in a further step to bring students closer to the new trends in the 4.0 industry.

In conclusion, it is an innovative exercise in its methodology and innovative in its objectives. It takes advantage of the necessary consolidation of theoretical concepts, which in a subject with a strong physical and mathematical load, such as the mechanics of the continuous medium, could otherwise be too far removed from immediate experience, with the development of the most important transversal skills for the development of the engineering profession.

2. Project description

The following sections describe the two course projects mentioned above, corresponding to the consecutive and independent subjects: Continuum Mechanics and Strength of Materials.

2.1 Continuum mechanics' coursework

The coursework consists in the design, optimization by FEA, prototype construction and laboratory testing of a simple mechanical tool. Several tools are defined to avoid repetition of the problem from one semester to the next one: nutcracker, brake handle (see Fig. 1), hook, elastic tweezers, flat wrench, crown-cap opener, etc. having to accomplish different technical requirements depending on the case.

Whatever the semester version, some contents are prescriptive in the study. These common contents are summarized in Table 1.

<u>Dynamics and chronology</u>:
The wording of the coursework is available to students from the very beginning of the course (15 weeks long, see Table 2), so that the first design and research stage can be early started.

After the global mid-term test (week #8), all students take the first contact with a finite element software in a 2 hours long practice session (week #9). Two weeks later (week #11) a coursework tutorial class takes place. The teams are requested to present the work made to date (10 minutes long at the most). A preliminary draft report containing sections 1 and 2 of Table 2 should be delivered. Any mistake or confusion is fixed by the professor and every team is guided to proceed with the rest of the work.

Three weeks later (week #15), during the last

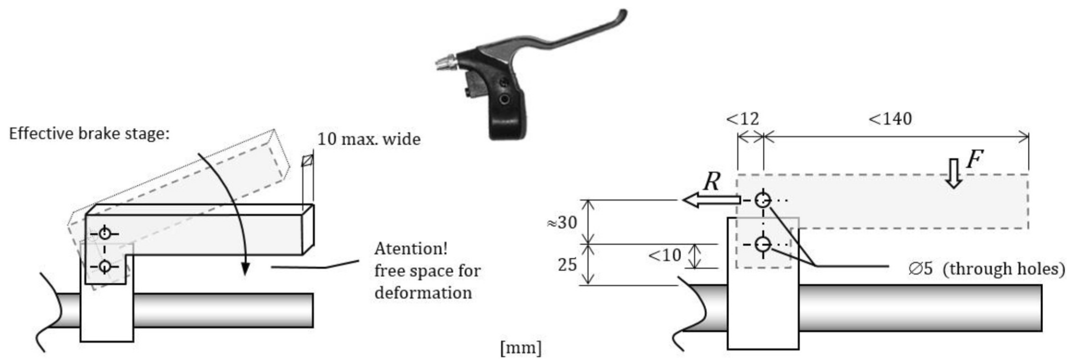


Fig. 1. Scheme of one of the tools to be designed: brake handle (dimensions in mm).

week of the course, the final presentations and experimental tests of the prototypes take place. The coursework must be orally presented for 15 minutes at the most. In order to prompt students to focus on speech efficiency, every out-of-time minute reduces the coursework grade in 1%. The final presentation should not be descriptive-type, but justifying-type. Any aspect of the work should be justified and argued by any one of the team members. One single grade is issued for every team, shared by its members, in order to prompt the three members to work as a real team. Every member of the team should be able to present the whole work content. The professor may arbitrarily decide which member will be presenting in every moment. Normally, only one of the members is prompted to present the whole coursework. After the presentation, the professor may address questions to any member of the team in order to evaluate the comprehension level of the subject.

The final purpose of this coursework is to achieve a deep comprehension of continuum mechanics and its practical application to engineering by means of the finite element method. The oral presentation of the coursework should be focused on showing the deep comprehension of the subject.

After the presentations, the experimental tests are carried out with the prototype. The report should then be finished in situ, by adding the experimental results, the results correlation with expected values and the conclusions. After this, the final report is delivered. Every team must deliver a single report.

Grading:
As shown in Table 2, the coursework grade ponderation is 17% of the whole course grade, where 2% comes from the preliminary tutorial class and the 15% remaining corresponds to the final oral presentation, the prototype testing and the written report.

Table 1. Contents of the Continuum Mechanics' study

1. RESEARCH AND EARLY DESIGN STAGE	Basic function of the tool. Key parameters and functioning mechanics. General requirements. Standards.
	Materials: availability, workability, properties, cost, recyclability, test results, etc.
	Nominal and ultimate required loads. Dispersion and characteristic values.
	Preliminary design. Prototyping technology.
2. THE FINITE ELEMENT MODEL	Model domain and **boundary conditions**. Idealizations and numerical singularities.
	Model features: finite element types, material models, **meshing**.
	Reliability of the results. Critical points and mesh refining.
	Validity of the linear and small displacements hypotheses. Is the non-linear solving procedure needed?
3. ANALYSIS OF RESULTS	Displacements field. Maximum values.
	Principal stresses and directions distribution.
	Failure criterion. Equivalent stresses distribution.
	Safety factor and failure load.
4. DESIGN OPTIMISATION, PROTOTYPING, TESTING AND CONCLUSIONS	Design optimisation process.
	Analysis of final results.
	Final design, drawings, and prototyping process.
	Budget, environmental impact and sustainability.
	Nominal and destructive tests. Results correlation. Conclusions.
	References and bibliography

Table 2. Grading and chronology of the Continuum Mechanics' course

Week:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	
Course event:	**Publication of the coursework wording**		1st lab session		2nd lab session			Global mid-term test	3rd lab-session: The FE Method		4th lab-session: **Coursework tutorial class**				5th lab-session: **Coursework presentation**	End-term exam
Task: Grading:			3%		3%			16%	1%		**2%**				**15%**	60%
Research and initial design																
FEA modelling																
Design Optimization																
Prototyping																
Presentation, tests and report																

Contest:
The best teams are awarded attending to the design efficiency, innovation, originality, creativity, sustainability, rigour, neatness, smartness, etc. The prize consists of an increase by 10% of the global subject grade for each member of the team, provided that a global pass grade was achieved before adding the prize. In case the final grade gets outstanding level, then the Honour Grade is awarded as well. Professors decide on the awarded team/s after reviewing and publishing the whole grades of the subject. The decision is published in virtual campus.

Finally, the coursework wording includes the following note to ensure that the students become aware of the final aim of their work. *IMPORTANT NOTE: The final aim of the coursework is to assess the deep comprehension of the physical phenomena studied in this subject and its practical use through the finite element method and the laboratory testing of prototypes. The oral presentation of the coursework should be focused on showing the comprehension of the following theoretical concepts. In particular:*

- *the displacements field;*
- *the strain and stress tensors;*
- *the elastic problem;*
- *the materials' constitutive models;*
- *the boundary conditions;*
- *the reliability and limitations of the finite element method;*
- *the elastic failure criteria and the safety factor.*

The particular ANSYS procedures have NO interest, but the proper definition and analysis of a finite element model.

2.2 Strength of materials coursework

The course project proposed in the Strength of Materials course consists in designing and constructing a structural beam following the scheme shown in Fig. 2. It can be observed that the beam is simply supported at A and B, and it has to carry a point load (P) applied near the mid-span (point C). Geometric restrictions are imposed to the beam design in order to make the project more interesting: (i) end supports are located at different levels; (ii) the beam has to overcome two 50 mm squared obstacles (O and O'); (iii) the longest straight part of the beam is limited to 400 mm; and (iv) the cross-section of the beam cannot be a commercial one (i.e., the cross-section should be transformed in some way after buying the pieces that will make up the beam). Students are free to design any beam accomplishing the just mentioned restrictions. There are, however, two additional conditions concerning the beam performance: (i) the overall strength safety factor with respect to the given load (P) should be in the range from 1,5 to 2,5; and (ii) the maximum vertical displacement at point C should be lower than 15 mm.

Dynamics and chronology:
The tasks to be performed by students during the project are presented in the subsequent paragraphs in chronological order. In Table 3, it can be observed that the structure of the coursework is very similar to that presented in the previous Section. In fact, part of the following explanations, especially those concerning materials testing and construction, also apply to the Continuum Mechanics' coursework.

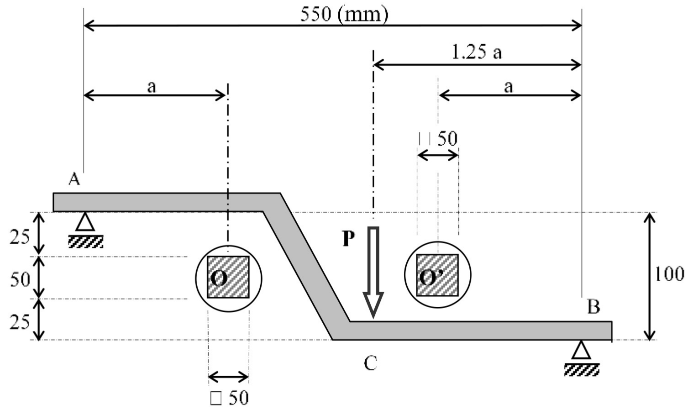


Fig. 2. Scheme of the beam to be designed (dimensions in mm).

Table 3. Grading and chronology of the Strength of Materials' course

Week:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	
Course event:				1st lab session		2nd lab session	Global mid-term test	**Publication of the coursework wording**	lab-session: The FE Method		4th lab-session: **Coursework tutorial class**				5th lab-session: **Coursework presentation**	End-term exam
Task: Grading:				2%		2%	20%		2%		**2%**				**12%**	60%
Research of information																
Preliminary design.																
Materials testing and design optimization.																
Prototyping and displacement calculation.																
Presentation, tests and report																

The first step is to carry out a preliminary beam design (weeks #9 and #10 in Table 3). This involves to set the beam longitudinal axis geometry; perform a structural analysis that will provide with the internal forces needed for strength design (axial and shear force, and bending moment); choose the material that will be used for construction; and design the shape and main dimensions of the cross-section. The project starts at mid-term (week #8), when students know the theoretical bases required to tackle these first tasks. In fact, this part of the project helps them to consolidate most of the theoretical concepts dealt within the first part of the course.

The most common design resulting from this first stage is a three parts beam, as depicted in Fig. 3, made of wood, aluminium or steel. The beam can show constant or tapered cross-section. Different geometries are chosen for the section, being rectangular, rectangular hollow, T or I cross-sections the most commonly used options. Nevertheless, there are always motivated students presenting interesting designs, such as: reinforced mortar or plaster beams, composite beams or 3D printed beams.

All the preliminary work is discussed in a first oral presentation to the professor and the other teams of the course (week #11). At this point, professors review the proposed designs and calculations, and give advice on the next steps of the project: construction and final presentation.

The construction phase starts with students buying the materials needed to build the beam. These materials are tested to get their mechanical properties (weeks #11 and #12). For instance, in case of a beam made of steel, a standard tensile coupon test is performed to know its Young modulus and yield stress. This is a way to introduce students into testing techniques for quality control of materials.

Material tests usually result in mechanical properties different from the nominal values used in the preliminary design. This makes students to revise the cross-section dimensions, and even the cross-section shape, to ensure that the final safety factor falls within the prescribed range. It is an interesting iterative job involving students and material suppliers.

Once the design is definitively set according to the real material values, students proceed to construction (weeks #13 and #14). They are asked to build their beams at home with their own tools, or at the laboratory with the tools provided by the department. This ''homemade'' construction is feasible in case of wood and aluminium beams, if no welding is needed. In case of students working on a beam made of steel, where welding is usually applied to assemble the different parts, or students that believe that are not capable to build the beam themselves, it is allowed to contact a professional to carry out the construction. This makes things easier, but students have to deal with a supplier again, which is always a challenge for them.

Students combine construction with the last steps of design, which involve: joint design and displacement check. On the one hand, approximate calculations are carried out to verify the strength capacity of the joints between beam parts (see Fig. 4), and connections between cross-section parts (for instance, the connections between web and flanges in an I-beam). On the other hand, the vertical displacement at point C (Fig. 2) should be determined to check that it does not exceed 15 mm. The displacement prediction is usually performed twice, by means of hand calculation applying Castigliano's second theorem, and by means of the Finite Element Method (see Section 3.2).

In the project development process, students should write a report explaining the technical decisions made by the team about design and material, describe the structural design, and provide complete analysis of the beam by applying theory of Strength of Materials. Specifically, the basic theory of beam elements must be applied: internal force determination, section design, verification and optimization, stress analysis and safety factor calculations, and displacement analysis.

The project closes with a second oral presentation and a final experimental test of the beam. In the presentation, students summarize the content of the written report to a small committee of professors, who will participate in the assessment of the coursework. Oral presentations are organized in the way outlined in Section 2.1. Interesting discussions take place during these presentations concerning design issues and correctness of theoretical calculations. Finally, beams are tested as described in Section 3.1. Two experimental results should be verified: (i) students have to check whether the vertical displacement under nominal load is similar to the value resulting from calculations; and (ii) the experimental ultimate load should be compared to the predicted one. After the test, students write a short discussion on the experimental results and submit the report.

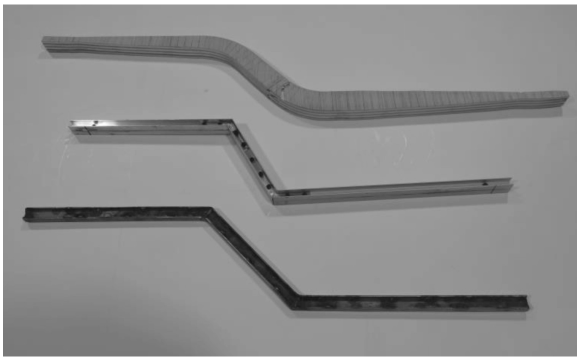


Fig. 3. Typical three parts beams.

Fig. 4. Joint between two parts.

Grading:
As shown in Table 3, the coursework grade ponderation is 14% of the whole course grade, where 2% comes from the preliminary tutorial class and the 12% remaining corresponds to the final oral presentation, the prototype testing and the written report.

3. Experimental setups and numerical tools

3.1 Experimental setups

In both project works, each team has to build the component that they have designed and to test it.

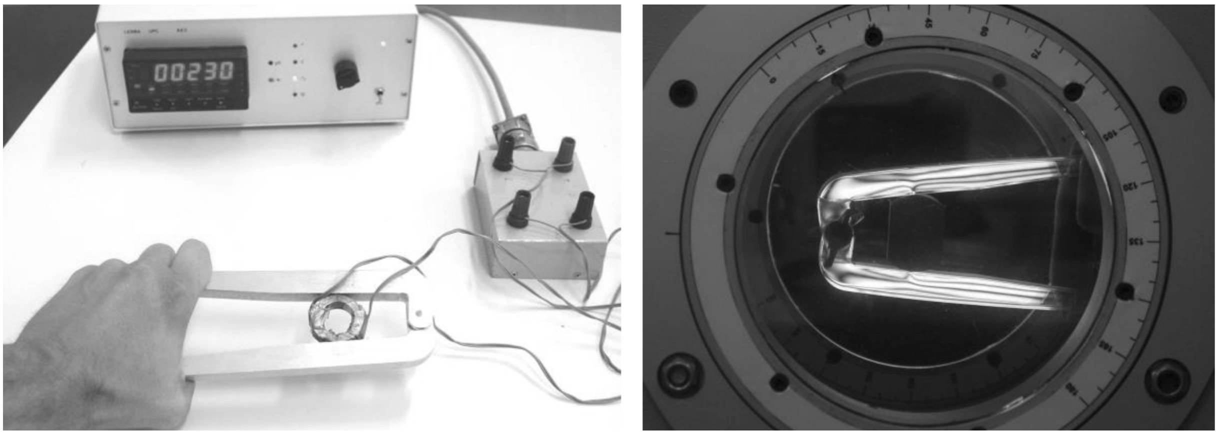


Fig. 5. Testing examples of Continuum Mechanics coursework. Aluminium and methacrylate nutcrackers

For doing the test properly the department has designed and build special tooling.

In Continuum Mechanics, there are different devices that are defined changing each semester. Up to six testing devices have been designed and build in order to measure the applied forces or reactions according to the requirements of each case.

As an example, Fig. 5 shows the nutcracker testing case. A simple strain-gauge device was designed to measure the force applied by the nutcracker to the nut (Fig. 5 left). Moreover, if transparent materials are chosen by students to build the tool, as methacrylate, they are invited to use the photoelastic technique as well (Fig. 5 right).

In Strength of Materials, the type of element is always the same, see Figs. 2 and 3. However, the dimensions vary from one semester to the next: distance and height between the supports. In addition, the position of the force application point and the value of the force, vary from one team to the other, as a function of the initial letter of the name and family name of the team member with the highest ID number. The testing device consists of: a base plate slot platen that allows to clamp all the elements in different positions; two columns, which hold the supports at an adjustable height; a pneumatic cylinder that generates a force adjustable through the air pressure between 0 and 2000 N. The force is measured with a force transducer mounted at the mobile end of the pneumatic cylinder, and the vertical displacement of the section of the beam where the force is applied, is measured with a displacement transducer (see Fig. 6). Lateral guides assure that the displacements of the beams are in the vertical plane.

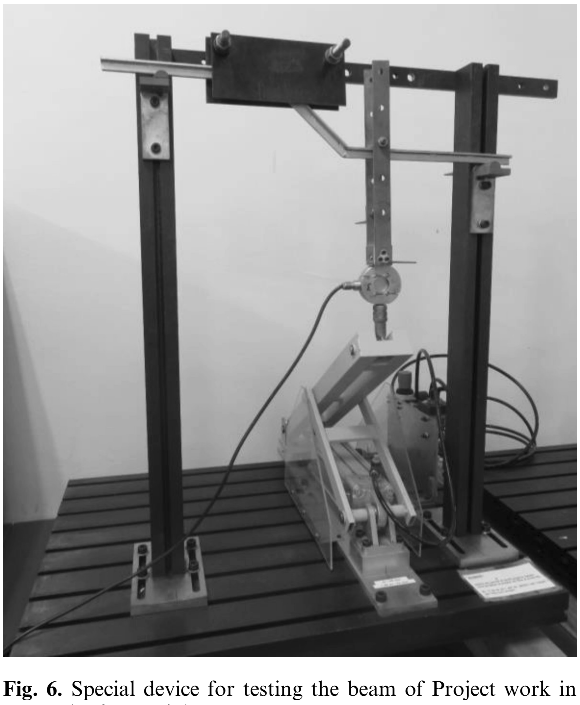


Fig. 6. Special device for testing the beam of Project work in Strength of Materials.

The beam has to withstand the service load specified without any type of damage, and the displacement under service load has to be measured and compared with the analytical one, previously calculated by each team. Finally, the beam has to be loaded until failure, and the failure load and type of failure have to be compared with the ones predicted by the team.

3.2 The finite element analysis

During the course projects, the finite element method is used as a numerical tool in order to consolidate all theoretical concepts of the subject. In each one, students have to deal with different and complementary engineering problems. The finite element analysis is also used to analyse and compare the differences obtained between a linear and a geometrical nonlinear analysis, which allows the consolidation of complex theoretical concepts.

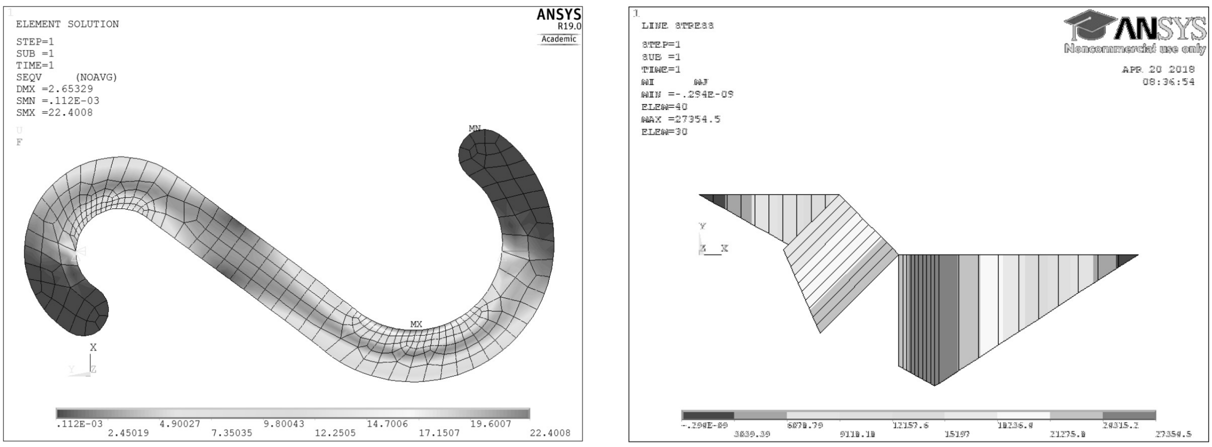
For Continuum Mechanics course projects, a finite element analysis is done to optimize a 2D part. Therefore, students must deal with the definition of the boundary conditions of a two-dimensional plane stress finite element model. The usage of FEA provides a more optimized solution. Consequently, students can face a real life optimization engineering problem which, in fact, is a key factor to consolidate and increase their learned knowledge and motivation. Furthermore, a finite element analysis can be used to introduce some advanced theoretical concepts, such as contact algorithms or topology optimization, which will probably be a relevant optimisation technique in a few years with parts obtained with additive manufacturing processes. On the other hand, in the Strength of Materials project students use FEA to obtain the structural response of a beam member. Therefore, beam elements are used to solve the problem. The finite element analysis is done to calculate the efforts and deflection of the member. Consequently, the students can compare and validate their analytical calculus with FEA results obtaining the feedback of their work and learning progress.

In both projects, students are encouraged to introduce the material stress-strain relationship obtained through experimental tensile or flexural test in order to approximate as much as possible the course project to a real engineering case. Finally, the experimental and numerical ultimate loads are compared. Consequently, students have an experimental feedback to know if their finite element model has produced an acceptable prediction of the member structural response. Furthermore, this comparison also gives them the chance to understand the simplifications used to translate the experimental real conditions to the boundary conditions of the numerical model.

4. Validation of the methodology

We could now ask ourselves whether all the effort in carrying out the work—both by the student and by the teacher—has really been useful, that is, whether, as we said in the introduction, combining practice, theory, simulation and experimentation is really useful and beneficial for learning.

Based on surveys to students conducted by the university at the end of the semester, it can be concluded that the work has really helped to deepen the concepts seen in classes (sometimes very theoretical). Students also find very interesting the fact that they are facing—perhaps for the first time—a real problem similar to those they will have to solve as engineers. In fact, it is intended that the course projects—both in Continuous Mechanics and in Strength of Materials—include a significant part of the content seen in class. The general structure is common to both projects, and the fact that prior to the presentation they have a tutorial class (4th laboratory session) as a guide, is highly valued. Reality is often not exactly how a theory class has presented it, sometimes the problem has been simplified or idealized. There are unforeseen events, mistakes, failures of one's own and others' own, etc. With all this in mind, they will have to face the problem and find a solution. This will be evaluated along with their oral presentation and the testing results. The overall assessment of the work is generally positive, but there are different opinions on the weight that the coursework grade should have in the overall assessment of the subject. We have already commented on the weight given to work. Most students agree that it is low, because the time and effort required does not correspond to the percentage of final grade earned. Some of them believe that the presentation, defence and testing



a) b)

Fig. 7. FEA results: (a) Von Mises stress distribution on one of the tools to be designed: a hook; (b) Bending moment diagram of one of the beam systems designed.

of the model should be sufficient for the overall assessment of the student, making the existence of a final examination of the subject unnecessary; it is understood that the work itself is already a kind of final examination.

Below are some specific answers to survey regarding coursework:

About *Continuum Mechanics* Coursework

- "I find it a very interesting work that allows us to apply the concepts of class in a useful way"
- "The project is very interesting, practice complements theory"
- "The best work I have ever done in my curriculum"
- "It is very well organized and that makes you get interested in it and, fortunately, you can learn a lot more than by writing exams. The project helps a lot to get it".
- "Because of the workload involved, I think the weight in the final grade should be higher".
- "The project was the most interesting thing of the course. A more extensive work could replace the final exam".

About *Strength of Materials* Coursework

- "It is a very good tool for consolidating knowledge".
- "It is very interesting to learn how to work in team and to apply theoretical concepts".
- "It is very motivating. Most of the contents of the subject are involved in the project".
- "It should have a higher weight in the global evaluation because it means a lot of work".
- "I think the assessment of the project should replace the final exam, as most of the contents of the course are included in it".
- "I consider that a project including construction of the structural element, writing report with analysis and oral presentation should have a higher percentage on the final mark".

For both subjects, the relationship between coursework scores and written exam's scores has been analyzed. A multiple-choice exam including short questions about theory and problems is done at midterm. The written final exam has three parts: theory and two problems. Results in Continuum Mechanics are plotted in Fig. 8. Table 4 shows results in Strength of Materials. Both are data from the 2017–2018 academic year, second semester.

It can be seen that:

1. Graphs (a) and (b) are similar.
2. Most marks of the coursework range from 7 to 9.

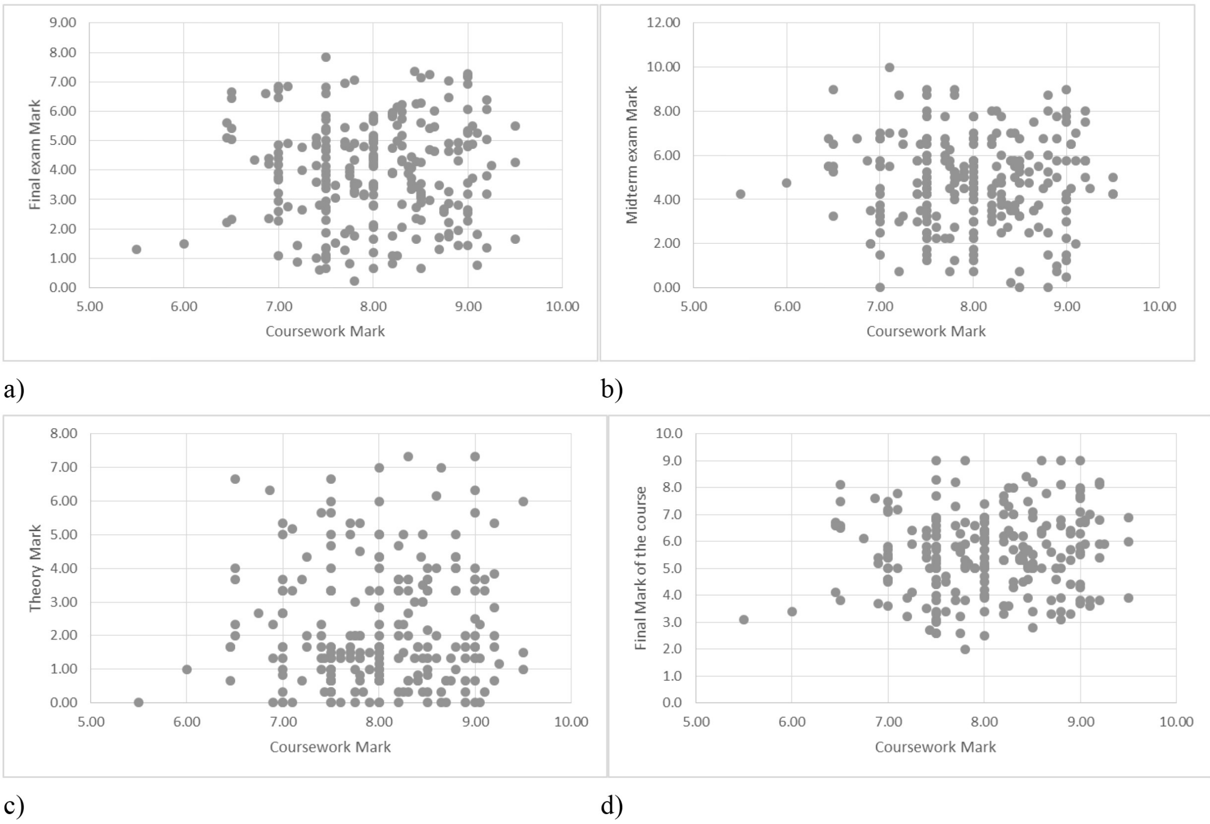


Fig. 8. Comparison of Marks: (a) Coursework vs Final exam; (b) Coursework vs Midterm exam; (c) Coursework vs Theory; (d) Coursework vs Final Mark of the course.

Table 4. Strength of Materials' score

The best Final Marks of the course (≥8)			The best Marks of coursework (≥9)		
Final exam	**Final Mark**	Coursework	Final exam	Final Mark	**Coursework**
8.75	**8.32**	8.80	4.83	5.40	**9.00**
8.52	**8.61**	7.80	4.55	5.96	**9.00**
7.78	**8.10**	7.51	6.72	7.29	**9.50**
8.75	**8.82→9.00H**	8.50	6.25	6.74	**9.10**
7.75	**8.34**	7.60	3.30	4.40	**9.00**
7.78	**8.16**	7.60	4.43	5.66	**9.00**
8.08	**8.42**	8.80	2.42	4.73	**9.50**
7.27	**8.17**	8.90	5.98	6.10	**9.00**
7.00	**7.97**	8.50	6.67	6.70	**9.00**
8.83	**8.82→9.00H**	6.00	3.45	4.60	**9.00**
8.22	**8.59**	9.5	5.75	6.45	**9.00**
8.22	**7.89**	8.00	3.93	4.59	**9.50**
8.88	**8.07**	9.10	8.22	8.59	**9.50**
7.10	**7.97**	8.00	8.88	8.07	**9.10**
7.80	**8.20**	8.00	3.08	5.03	**9.50**
8.18	**8.62**	8.00	6.72	7.87	**9.10**
7.93	**8.25**	8.61	5.17	6.10	**9.00**
8.67	**8.86→9.00H**	7.60	5.00	5.99	**9.00**
7.83	**8.48**	8.00	6.78	7.33	**9.50**
7.75	**8.22**	8.80	5.85	6.64	**9.00**
			7.33	6.94	**9.00**
			8.25	7.89	**9.00**

3. The marks of the Theory part are lower than those in the exam as a whole.
4. The final marks of the subject are higher when the mark of the coursework and laboratory is incorporated (experiential learning).

Columns 1-2-3 in Table 4 show the best Final Marks of the course compared to Final exam and coursework Marks. Columns 4-5-6 show the best Marks of coursework compared to Final exam and Final Mark of the course.

As it can be observed, not many connections can be seen within the data, in most cases; with one exception, the coincidence between columns 1 and 2. Sometimes good students, those with the best Final Marks (column 2), do not get the best Coursework marks (column 6). This is due to different reasons. For instance, it can be that the experimental result of the designed element was not as expected, or maybe they took risks with the design; but this is also part of the learning process.

Upon this issue, we conclude that there is no correlation between coursework marks and examinations' scores. In this regard, the following considerations can be made:

1. The coursework mark covers (a) the construction and design of the element, (b) the report and analysis, (c) the presentation and defence, and (d) the agreement between theoretical and experimental results. Whereas, written exams essentially evaluate part (b).
2. The mark of the coursework is given to the team, and it is often observed that the degree of involvement of each member in the project is uneven.
3. In order to achieve a correlation between the coursework score and the examinations' score (is this an objective?), more time should be allocated to the oral presentation, and teachers' questions should be focused rather on the comprehension of the theoretical and analytical concepts.

5. Conclusions

The evaluation criterion is one aspect to be improved. Professors should realize that the students' enthusiastic attitude, their commitment or the correctness of the written report is not the real goal, but only the right path to the real goal: learning. Therefore, effective learning should be the only aspect being graded. On the other hand, students should realize that the aim of the coursework is not to play engineering for getting the best design, but it is about getting the best learning through playing that game.

The comments made by the students help to verify that the coursework has really contributed to achieve the objectives that we set out to fulfil in the beginning. The combination of theoretical concepts seen in class with real examples has helped to improve the learning of the subject, and the students are satisfied and more motivated; although the overall grade obtained in the subject is not related to the specific grade of the work.

The grades of the coursework are higher than the ones obtained from the written exams. Teachers tend to mark the project taking into account the work done, as a recognition of the effort and interest demonstrated by the team. Some students consider that the weight of the work grade is low in relation to the time they spend and the learning outcome they experience. It is difficult, however, to identify the degree of involvement of each member of the team, since the number of groups is over 60 (about 240 students each academic year).

References

1. D. Jensen, J. Wood and K. Wood, Hands-on Activities, Interactive Multimedia and Improved Team Dynamics for Enhancing Mechanical Engineering Curricula, *International Journal of Engineering Education*, **19**(6), 2003, pp. 874–884.
2. I. de los Ríos, A. Cazorla, J. M Díaz-Puente and J. L. Yagüe, Project-based learning in engineering higher education: two decades of teaching competences in real environments, *Procedia Social and Behavioral Sciences*, **2**, 2010, pp. 1368–1378.
3. M. Forero and M. D. Gilchrist, Innovations in Undergraduate Engineering Mechanics Education: Use of Team-Based Research-Led Project Methods for Large Student Cohorts, *International Journal of Engineering Education*, **27**(4), 2011, pp. 821–839.
4. T. Joyce, I. Evans, W. Pallan and C. Hopkins, A Hands-on Project-based Mechanical Engineering Design Module Focusing on Sustainability, *Engineering Education*, **8**, 2013, pp. 65–80.
5. K. Lulay, H. Dillon, T. A. Doughty, D. S. Munro and S. Z. Vijlee, Implementation of a Design Spine for a Mechanical Engineering Curriculum, *American Society for Engineering Education* (122nd ASEE), 2015, Paper 11406.
6. N. J. Hunsu, B. Abdul, B. Van Wie, O. Adesope and G. R. Brown, Exploring Students' Perceptions of an Innovative Active Learning Paradigm in a Fluid Mechanics and Heat Transfer Course, *International Journal of Engineering Education*, **31**(5), 2015, pp. 1200–1213.
7. K. Giridharan and R. Raju, The Impact of Experiential Learning Methodology on Student Achievement in Mechanical Automotive Engineering Education, *International Journal of Engineering Education*, **32**(6), 2016, pp. 2531–2542.
8. N. B. Pour, D. B. Thiessen, R. F. Richards and B. J. Van Wie, Ultra Low-Cost Vacuum Formed Shell and Tube Heat Exchanger Learning Module, *International Journal of Engineering Education*, **33**(2A), 2017, pp. 723–740.
9. D. C. Lagoudas, J. D. Whitcomb, D. A. Miller, M. Z. Lagoudas and K. J. Shryock, Continuum Mechanics in a Restructured Engineering Undergraduate Curriculum, *International Journal of Engineering Education*, **16**(4), 2000, pp. 301–314.
10. A. Silva and L. Faria, Two Approaches to Design Teaching in a Mechanical Engineering Curriculum, *International Journal of Engineering Education*, **28**(2), 2012, pp. 474–483.
11. A. Brown, D. Jensen, J. Rencis, K. Wood, J. Wood, C. White, K. K. Raaberg and J. Coffman, Finite Element Learning Modules as Active Learning Tools, *Advances in Engineering Education*, Winter 2012, pp. 1–29.
12. C. J. Lissenden and N. J. Salamon, Design Project for Advanced Mechanics of Materials, *International Journal of Engineering Education*, **20**(1), 2004, pp. 103–112.
13. K. K. Bhatia, Application of Finite Element Software to Bridge the Gap between Hand Calculations and Experimental Results in Undergraduate Heat Transfer Education, *International Journal of Engineering Education*, **25**(6), 2009, pp. 1092–1096.
14. D. Holland, C. Walsh and G. J. Benett, An Assessment of Student Needs in Project-Based Mechanical Design Courses, *American Society for Engineering Education* (120th ASEE), 2013, Paper 7038.
15. C. Iorga and A. Desrochers, Development of a motorcycle frame as a problem-based learning experience in design courses for Mechanical Engineering students, Proc. 2014 *Canadian Engineering Education Association* (CEEA14) Conf., Paper 36.
16. F. Roure, M. Pastor, J. Bonada and L. Rodero, Interdisciplinary Engineering Project: Experimental and Numerical Optimization of a Sandwich Panel, *International Journal of Engineering Education*, **31**(1B), 2015, pp. 248–256.
17. A. Pradera-Mallabiabarrena, I. Merideno, A. Lopez-Arancibia and R. Anton, Multiple Approach Experimental Project for Engaging Students in Learning: Implementation and Assessment, *International Journal of Engineering Education*, **31**(5), 2015, pp. 1299–1308.
18. National Academy of Engineering. 2005. *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11338.
19. M. J. Prince and R. M. Felder, Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases. *Journal of Engineering Education*, **95**(2), 2006, pp. 123–138.
20. J. E. Mills and D. F. Treagust, Engineering Education—Is Problem-Based or Project-Based Learning the Answer? *Australasian Journal of Engineering Education*, online publication 2003-04, http://www.aaee.com.au/journal/2003/mills_treagust03.pdf.
21. VDI&ASME. 2015. Industry 4.0. A Discussion of Qualifications and Skills in the Factory of the Future: A German and American Perspective.
22. © 2018 World Economic Forum. The Future of Jobs. http://reports.weforum.org/future-of-jobs-2016/skills-stability/

Ma Magdalena Pastor Artigues is Associate Professor within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). She is the co-author, together with Professor Francesc Roure, of one educational multimedia web site published in 2009: PRISMATIC Learning about *Strength of Materials* (http://www.upc.edu/prismatic/). Her research interests focus on cold-formed steel structures and additive manufacturing.

Francesc Roure Fernández is Full Professor within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). He teaches *Strength of Materials*. His research is focused on thin-walled steel structures and numerical and experimental stress analysis. He has been Vice-director for academic policy (2001–2006) and Director (2007–2013) of the Engineering School.

Miquel Ferrer Ballester is Professor within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). He teaches *Continuum Mechanics* and *Structural Dynamics*. His research activity is currently focused on steel-concrete composite slabs, bio-mechanics of implants and seismic analysis of light steel-structures.

Xavier Ayneto Gubert is Associate Professor within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). He teaches Continuum Mechanics and structural analysis for the automotive industry. His research is focused on fatigue of materials and structures and numerical simulation. He has been academic director of the MIGIA master's degree in automotive engineering, and academic director of the NISSAN Motor Ibérica Chair in automotive innovation.

Miquel Casafont Ribera is Associate Professor within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). He teaches *Strength of Materials* and *Non-linear behaviour of Structures*. His main research interest is cold-formed steel structures: behaviour, computer modelling and experimental testing.

Josep Maria Pons Poblet is Professor within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). He teaches *Theory of Structures* and *Continuum Mechanics*. His main research is focused on historical buildings.

Jordi Bonada Bo is Serra Húnter Fellow within the Department of Strength of Materials and Structural Engineering at Polytechnic University of Catalonia (UPC). He teaches *Strength of materials and Analysis of Structural and Mechanical Components by the Finite Element Method.* His research interests are focused on structural analysis of thin-walled sections through numerical and theoretical models and additive manufacturing.